

# Deflection Measurements of a Thermally Simulated Nuclear Core using a High-Resolution CCD-Camera

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**Abstract.** Space fission systems under consideration for near-term missions all use compact, fast-spectrum reactor cores. Reactor dimensional change with increasing temperature, which affects neutron leakage, is the dominant source of reactivity feedback in these systems. Accurately measuring core dimensional changes during realistic non-nuclear testing is therefore necessary in predicting the system "nuclear" equivalent behavior. This paper discusses one key technique being evaluated for measuring such changes. The proposed technique is to use a Charged Couple Device (CCD) sensor to obtain deformation readings of electrically heated prototypic reactor core geometry. This paper introduces a technique by which a single high spatial resolution CCD camera is used to measure core deformation in Real-Time (RT). Initial system checkout results are presented along with a discussion on how additional cameras could be used to achieve a three-dimensional deformation profile of the core during test.

## INTRODUCTION

All space reactors currently being considered for near-term missions are compact, fast-spectrum systems fueled with highly enriched uranium. For this type of system, reactivity feedback is dominated by core deformation. A system to measure core deformation is currently under development at the Early Flight Fission - Test Facility (EFF-TF) at Marshall Space Flight Center (MSFC). Once accurate deformation measurement techniques are developed, the EFF-TF will be able to demonstrate the operational behavior of different reactor designs using non-nuclear testing techniques by combining experimental work with computational analyses. The non-nuclear tests will couple deformation measurements with nuclear calculations, making real time adjustments to the power delivered to prototypic core geometries. Through a series of Monte Carlo calculations, the core reactivity can be determined as a function of the physical core deformation as the core temperature increases. The reactor power transients can then be modeled using point kinetics. Application of real time measurements of the core deformation with kinetic calculations allows the core power to be adjusted automatically to match the response of an operating nuclear reactor. The EFF-TF is currently capable of simulating slow to moderate power transients (e.g. reactor startup) while realistically taking into account the dominant reactivity feedback mechanism.

Several different techniques can be used to measure core deformation. These techniques can be categorized into the following groups: Time of Flight (TOF) instruments, resistive instruments and optical instruments. For the current activity, a high-resolution optical CCD system was selected based on low cost, relatively simple integration into the test environment, and its outstanding spatial resolution. Unlike most Single Point Instruments (SPIs), the optical system is capable of taking multiple linear scans across the entire width and length of the core using only a single sensor. This option can be used to validate the uniformity of core deformation, providing reactor designers the ability to rapidly test configurations early in the design stage for core "hot spots". A typical indication of a "hot spot" is a greater deformation at a particular axial location that does not appear elsewhere along the same axis. Observation of a hot spot could indicate a design flaw or, more importantly, it could indicate defective or failed core materials. From a safety standpoint, the instrument currently under development can play a major role in future space nuclear reactor design.

## DEFORMATION

The measurement of deformation is one of several key elements necessary in successfully implementing and executing the EFF-TF reactivity feedback control system. The simulation is based on the theory that for a fast spectrum reactor, deformation is a direct indicator of how efficiently the reactor's neutron reflection mechanism is performing<sup>1,2</sup>. As the nuclear reactor heats up, the materials in the core begin to expand or deform. Material expansion corresponds to a negative reactivity due to increased neutron leakage. If the neutron multiplication factor,  $k$ , becomes less than 1, the reactor fission power decreases. As power decreases, the temperature of the core material also decreases, resulting in an overall contraction. This contraction reduces neutron leakage, introducing positive reactivity, and the power and temperature begin to increase once again. This cycle continues until a physical balance is reached. The reactor is said to be critical ( $k=1$ ) when each successive generation has the same neutron population. When the system is critical, a steady-state power output is achieved. Reactor control is provided by external rotating control drums placed symmetrically around the core perimeter. Each drum contains neutron reflector and absorber materials; varying the angular drum position regulates the neutron reflection/leakage by varying the amount of absorber in the reactor core. Using computer models, an optimum control sequence can be devised to simulate the startup transient and steady state operation. This algorithm can be optimized based on the following<sup>3</sup>:

- The reactivity worth of each control drum is determined by neutronic simulation using MCNPX<sup>4</sup>; during core operation, the simulated control drum angle provides a given reactivity insertion based on an empirical equation developed for the drum reactivity worth.
- Solution of the point kinetics equations provides the thermal power output for the simulated reactor as a function of the control drum position (positive reactivity insertion) and the total core deformation (negative reactivity insertion, directly related to core temperature).

Using this methodology, the simulated drum angle and measured core deformation serve as inputs to the reactor point kinetics equations, which are solved in real-time to control the power output in the non-nuclear reactor system. Figure 1 shows an image of the 100 kWt Safe Affordable Fission Engine (SAFE-100) heat pipe reactor model<sup>5,6</sup>, where a single width "cross-section" dimension (indicated as  $\Delta d$ ) in the y-axis is highlighted.

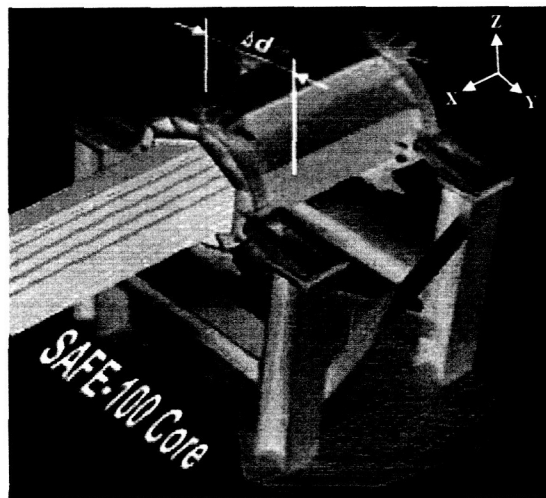


FIGURE 1, SAFE-100 Core Width Cross-Section

Assuming the core is perfectly symmetric, the temperature distribution would be radially symmetric, therefore generating symmetric radial expansion. The deformation ( $\Delta d$ ) is the missing variable necessary to complete the power calculations for the next simulation cycle. By continuously monitoring cross section deformation at a selected axial location and feeding it back to the reactor point kinetics equations, the behavior of a real nuclear reactor can be simulated using non-nuclear testing techniques. For the current

model, the required measurement resolution is 100 microns or better to successfully simulate the power transient of a fast spectrum nuclear reactor. Various techniques can be employed to measure core deformations; they must be evaluated on a case-by-case basis as prescribed by the environment, complexity, cost, and resolution accuracy.

## THE DETECTOR

The test environment dictates acceptable methods for gathering deformation data to be used in the reactivity feedback calculations. At the EFF-TF, non-nuclear testing is performed in a vacuum to simulate the space environment and to protect the graphite heater elements from oxidation. This sets the baseline for selecting the hardware used for measuring the deformations in the reactor simulator. The vacuum environment eliminates techniques such as ultrasound and other low frequency measurement devices. Additional requirements, including simplified non-intrusive setup, low maintenance, high temperature operation and overall low cost, significantly narrows the field. An optical Charged Couple Device (CCD) was chosen to measure core deformation at the EFF-TF. The vacuum environment requires the CCD device be located outside the vacuum chamber, positioned with a clear view of the core through a fused silica window. Figure 2 shows the hardware setup as well as the optimal camera view required to record changes in the core width (across the y-axis).

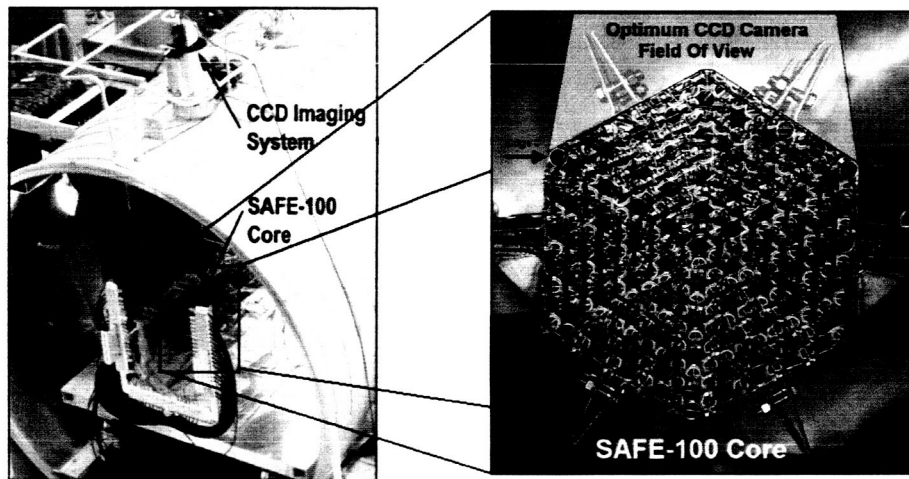


FIGURE 2, The hardware setup

The optical sensor used to measure core deformation is a Kodak 6.1 mega-pixel camera<sup>7</sup> (using 9 micron technology) consisting of a CCD array of 3072 by 2048 pixels. This large sensor array provides excellent spatial resolution, making the camera ideal for viewing a variety of object sizes and shapes. The sensor is technically specified as  $9 \times 9 \mu\text{m}$ , but in actuality this pixel resolution can differ significantly depending on the test setup, i.e. the distance to target and type of lens used. Using simple analyses, the correct lens can be determined based on the relation between the optical path and the projection area of the object. The lens used in the initial testing is a Nikon 70-210 mm. This lens has a narrow viewing angle, capable of focusing on relatively small objects at very long distances. The lens/camera combination produces a pixel resolution of  $\sim 90$  microns when aligned to view the entire core cross section of  $\sim 266$  mm. Although this resolution is a factor of ten larger than the CCD pixel resolution, it still meets the reactivity feedback model requirement.

## THE ENVIRONMENT

Setting up a high-resolution camera system for detecting object deformations in the 100-micron range is a difficult task. Adding the environmental variables introduces many unwanted optical interferences that can only be studied with extensive testing and analysis. Sources of interference can be categorized as follows:

## I. Spatial interference

- a. Lens effect as the glass window deforms under vacuum.
- b. Positional variation due to chamber deformation under vacuum.
- c. Variable refractive index depending on which medium is used during test (Air, Vacuum, etc.).
- d. Blurring/artificial motion of the CCD Field of View (FOV) due to low frequency vibrations.

## II. Thermal interference

- a. Reactor thermal emission above 750 °C affects the detection efficiency.
- b. Thermal “heat wave” effect introduces “jitter” in image.

Knowing that these elements are present, countermeasures can be readily applied to reduce or eliminate their impact, improving the overall measurement accuracy. The importance of corrective action for spatial interference is demonstrated by a use of a simple example. Figure 3 clearly illustrates the difference in camera detection by comparing chamber conditions of atmospheric pressure versus vacuum. The data acquired under vacuum conditions ( $10^{-4}$  Torr) is influenced by deformation and a varying set of environmental interference since the overall dimensional calibration was made at atmospheric pressure conditions. Since the vacuum chamber environment variables can be changed (varying chamber pressure and type of atmosphere), a defined study has not been performed to examine the contribution of each source to the total interference. Rather, a three step operational procedure has been established to correct for external interference prior to initiating deformation measurements:

- 1) Use mechanical calipers to establish specific core dimensions at predetermined locations.
- 2) Establish the steady state environmental conditions required by the test.
- 3) Apply the caliper measurement to the CCD image creating the “calibration factor” (length/pixel).

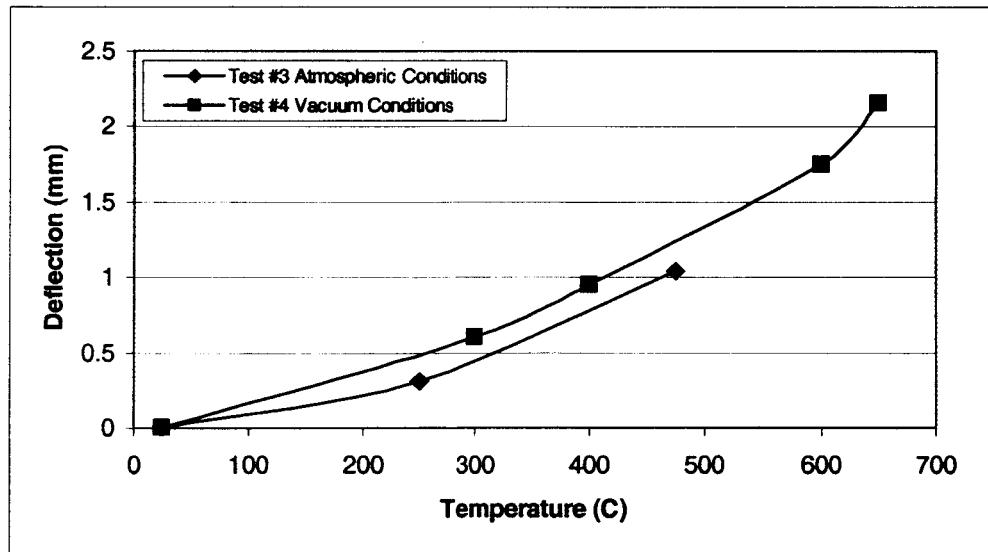
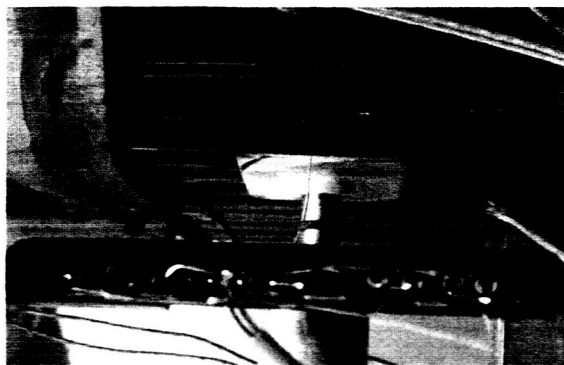


FIGURE 3, Deformation Readout in Different Environments

Using this procedure each time a test is conducted, the interference generated by the environmental/structural variables can essentially be eliminated. Vibration interference is primarily due to water coolant circulating in flow channels placed on and around the vacuum chamber wall. When fluctuations occur in the water circuit, interference is visible in the deflection measurements system. This inference can be controlled since it typically occurs only while alternate water circuits are being toggled manually during test.

## EVALUATION

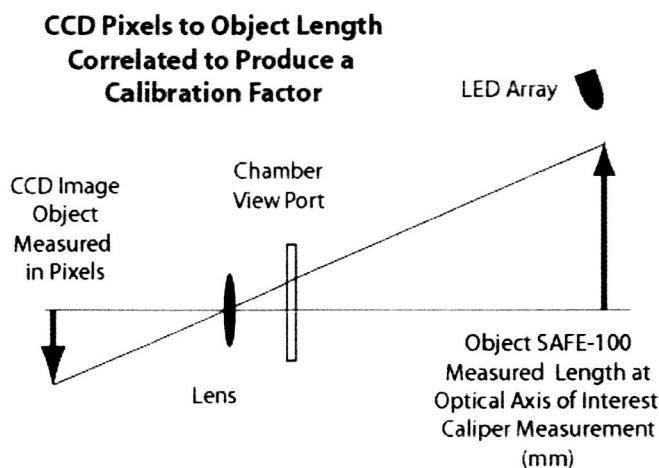
The Kodak CCD sensor selected is designed for detection in the visual spectrum with peak efficiency at 490 nm and decreasing sensitivity as wavelength trails into both the UV and IR regions. This sensitivity provides a good indicator of the type of light (wavelength) that should be used to illuminate the test article, maximizing the success of edge detection. Figure 4 shows the initial setup of the lighting system; an array of Light Emitting Diodes (LEDs) is positioned to illuminate the core axis along the heat pipe module of interest.



**FIGURE 4, Illumination Using LED System**

The benefit of using a single row of LEDs is that the beam can be accurately aligned to illuminate only the regions of interest. This eliminates stray reflections from pipes located both above and below the location of concern, reducing potential confusion of the automated data system that monitors core deflection. The core's outermost heat pipe modules were selected for illumination, providing an acceptable core cross-section or "width" for determining deformation.

After aligning the light source, measuring the core "width" with mechanical calipers, and establishing the required vacuum chamber environmental conditions, the CCD sensor calibration factor can be established. Following this sequence of events minimizes the effects of environmental influences on establishing the spatial resolution of the camera. Since the CCD sensor accounts for displacement in terms of number of pixels (3072 pixels horizontally and 2048 pixels vertically) a correlation or calibration factor is established. Figure 5 illustrates the general layout of the object, view port, lens and CCD sensor.



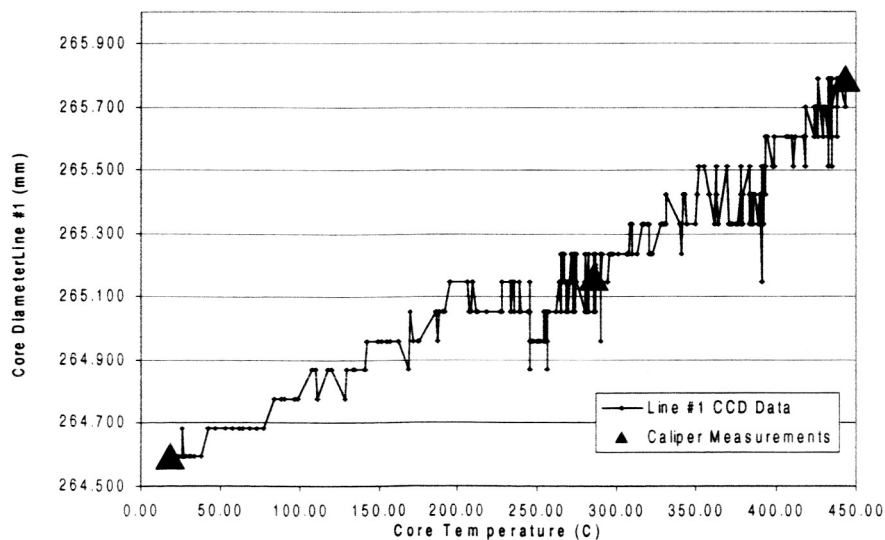
Typically, the CCD camera FOV is adjusted such that there is a 1 cm of additional viewing space to either side of the core; this space allows for continual tracking of the core edge as the core expands during heating (the image does not move off screen). As the camera collects images, a filter is used to detect the two sharply defined edges on each side of the core. Figure 6 shows the camera field of view where the two measured edges are illuminated. Measurement points are identified by E0 and E1.



**FIGURE 6**, Camera FOV during calibration

Using a computerized filter algorithm, the two points E0 and E1 are continuously tracked as the core expands and contracts. The screen capture shown in Figure 6 is referred to as the “zero frame”; it is used during the calibration stage to establish the length to pixel factor prior to starting the test. This “zero frame” is captured at room temperature under identical environmental conditions (as those to be used during testing) so that the previously mentioned “interferences” can be significantly reduced. The calibration factor is the ratio of the caliper measurement to the number of pixels between points E0 and E1 (on the core edges). Typical core width dimensions and pixel counts for the experimental geometry are 264.6 mm and 2865 pixels, respectively. The resulting resolution for the baseline camera setup is 0.092 mm. As power is applied during operation, the core slowly expands resulting in an increased number of pixels representing the core width.

With the setup complete, the next step is to verify the data produced by the CCD system (i.e. prove its real time ability to track edges and calculate deformation as the core assembly is heated). To validate the CCD system, a redundant instrument (in this case a caliper) was used to take measurements at precise core locations (E0 and E1) monitored by the CCD so that a comparison can be made. Tests were performed at room temperature, 300 °C and 450 °C with the vacuum chamber operated at atmospheric pressure so that caliper measurements could be taken. Figure 7 shows the initial test results. The CCD system produces continuous data shown as a solid line while discrete data points represent the caliper measurements.



**FIGURE 7**, The initial CCD validation using calipers

As seen in Figure 7, the CCD system and the caliper measurements match nicely throughout the temperature range tested, validating the systems capability to both track and measure core width deformation. This figure also clearly shows the increase in camera sensor noise as the core temperature increases. This noise effect is due to the heated air rising above the core creating waviness in the image. This interference cannot be eliminated while using an optical detector and non-vacuum conditions. For actual testing, this interference will not be an issue since all deformation measurements will be performed in a vacuum. This validation demonstrated that the camera system can be used to track deformation; however, it also showed that the resolution was limited to the jitter between pixels ( $\pm 92$  microns).

With a fixed CCD pixel resolution of 92 microns, one potential method to reduce jittering is to examine spatial averaging of more than one pixel per edge. The actual sampling edge of the cylindrical surface is not perfectly sharp but rather a "gray" transition between the core and background. By using a number of pixels distributed around the target location, a real time spatial average can be generated, increasing the measurement accuracy. Figure 8 provides a representation of this technique detailing multiple sampling points along one edge of the core with the target position identified by the arrow.

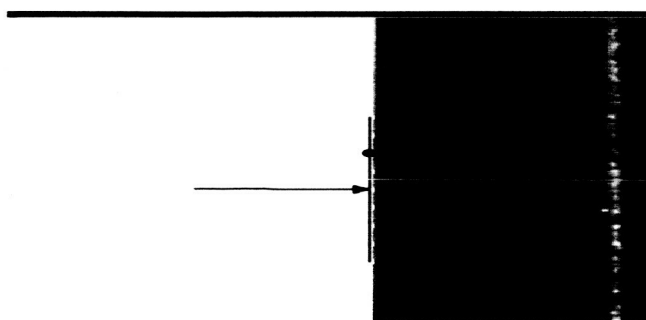
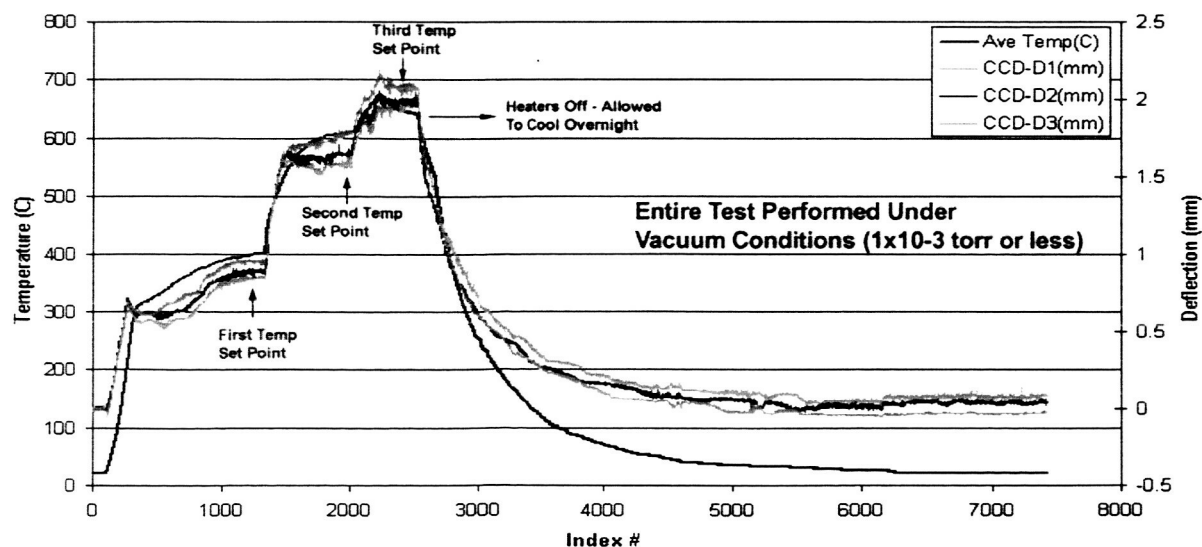


FIGURE 8, Edge - Axial Averaging Technique

Using a 30-point axial average, the pixel resolution can be improved by an approximate factor of five to 20 microns. Spatial averaging is an excellent way to increase the pixel resolution, but it must be understood that 30 pixels corresponds to approximately 3 mm along the length of the core. Caution must be taken in trading off the number of pixels used; using too many pixels in the averaging process can skew data since there will certainly be different expansion rates along the core axis (variation in heating, clamping, etc.). Figure 9 shows the results of the first full checkout test in which deformations at three separate core cross-sections were sampled. During this test, three temperature set points (400°C, 600°C and 650°C) were examined.



**FIGURE 9, The CCD Deflection Measurement vs. Temperature**

In Figure 9, the sampling lines are separated axially by approximate 25 mm (slightly different expansions are expected due to core geometry); each used a 30-point averaging technique to maximize pixel resolution. Adding a temporal averaging component to the spatial algorithm could possibly increase the resolution by another factor of five.

## **CONCLUSION**

Initial results have shown that a CCD camera can easily be used to detect relatively small deformations (<100 micron) on a prototypic reactor core geometry. This was achieved despite the camera being located a relatively long distance from the test article, viewing it through a fused silica window. By applying deformation data to the reactivity feedback controller, the power can be manipulated to mimic the behavior of a nuclear reactor. The demonstrated instrument was simple to set up, calibrate and maintain. In addition, the camera system has shown great design flexibility, fully capable of upgrades without redesign. If improved resolution <sup>was</sup> required, the system could be easily upgraded with the use of a large CCD array. This change would only require replacement of the camera, leaving operational procedures and software unchanged. Through its design flexibility, with the addition of two or more cameras (one camera per axis), a three-dimensional deformation mapping could be acquired and presented graphically. This would allow scientists and engineers the capability of viewing the deformation of the electrically heated core from many directions along the full axial length. For testing and validation of a nuclear reactor design, this technique can prove invaluable, providing transient and steady-state behavior and detecting thermal expansion problems very early in the design process.

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